Research Investigations for Fabrication of Electrochemical Energy Storage Devices through Additive Manufacturing

Synopsis

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Research title

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Summary

Nowadays, AM (additive manufacturing) methods are very popular because of their advantages over conventional methods, like lower capital costs, less wastage of raw materials and energy, improved part reliability, lower prototyping costs, the ability to manufacture a whole assembly in a single print, and minimum on-hand inventory, etc. Most electronic gadgets, electric and hybrid vehicles, aerospace electronics, and electronic components of spacecraft or satellites are powered by EESDs (Electrochemical Energy Storage Devices). Typically, EESDs consist of two current collectors, an anode, a cathode, and a separator. The manufacturing of EESDs takes place as electrodes and then fabricated as cells. In conventional methods, there is a requirement for a solvent, N-Methyl Pyrrolidone, which is used to make the homogeneous mixture of EESD fabrication materials. It is expensive, exhibits inflammable vapours, and is highly toxic in nature, which increases the capital cost and running cost of the manufacturing plant.

In the proposed research work, effort will be aimed at refining and standardising AM for EESDs. The proposed experimental includes the development and preparation of the material with the required constituents and their percentage in the mixture to fabricate the EESDs with the required parameters like size, shape, and capacity. A Cartesian type AM setup will be used to fabricate the EESDs to investigate the effects of controllable parameters of the material (like various compositions of fabrication material) and the AM setup (raster angle, raster width, and bed temperature). The above-mentioned designed and developed EESDs will be evaluated in terms of performance, cost, reliability, and safety in a variety of environments. Fabrication materials will include various ratios of constituent materials like thermoplastic materials (like poly lactic acid, acrylonitrile butadiene styrene, and polypropylene), conductive materials (like carbon nanotubes and graphene), and active materials (like lithium cobalt oxide, lithium titanate oxide and lithium iron phosphate). There is no toxic chemical in the proposed work, which will help to reduce the total fabrication cost of the EESDs. The rigorous testing of the EESDs includes mechanical testing (like tensile, compression, and impact tests),

chemical testing (like environmental, abuse, and stability tests), electronic testing (like load, ionic conductivity, and cycle tests), and surface morphology (like scanning electron microscopy and x-ray photoelectron spectroscopy). The proposed work will set a milestone for EESDs with cost reduction and fast prototyping. This will mark a step towards a new age of growth and innovation in India and a new milestone being achieved in the Make in India campaign and will make India self-reliant in the area of AM for EESDs. The proposed work's output would undoubtedly offer impetus to make the technology cost-effective so that it may thrive in the Indian market, making it an outstanding job facilitator and promoting the establishment of start-ups and entrepreneurs in India. Significant research & development is required to investigate new AM setup designs and fabricating process parameters in order to fabricate the EESDs at a high throughput at a low cost.

Introduction

Energy storage technologies, including mechanical, thermal, chemical and electrochemical energy storage, are key components in the energy conversion between various forms that are problematic to store into inexpensive and easy-to-use energy forms [1][2]. Electrochemical energy storage is one of several technologies for the development of practical energy devices that can convert and store electric energy in the form of chemical energy, as well as reverse the effects via electron and ion transfer between electrodes across separator [2]. EESDs (Electrochemical Energy Storage Devices) comprise different batteries, super-capacitors, and hybrid equipment. The development trend of EESDs is high gravimetric capacity, miniaturisation, multifunction, and integration [3]. These devices have applications in electric and hybrid vehicles, space crafts, pacemakers, etc. [4].

Most electronic gadgets, electric and hybrid vehicles, aerospace electronics, and electronic components of spacecraft or satellites are powered by EESDs because of their high gravimetric capacity. Already available EESDs consist of an anode, a separator, a cathode, and two current collectors assembled as multiple layers that are packed in cases based on the shape of the electrodes. EESDs are made in a controlled environment as moisture and high temperatures can negatively affect an EESD's performance, life span, and safety. EESDs have become a ubiquitous part of our lives as it powers most portable electronics with properties like small size and light weight, but at a higher cost.

Introducing the fundamentals of EESDs includes fabrication material, chemical, and electrical properties based on performance requirements and calculations. There have been significant recent efforts to develop EESDs with unconventional shapes and structural batteries to overcome form factor limitations. AM (additive manufacturing) shows encouraging advantages, including cost reduction, rapid prototyping and fabrication, the ability to create intricate 3D compositions, certain types of performance enhancement, and energy consumption reduction [5–8]. The AM works well for high-resolution fabrication of carbon nano-lattice structures, which can be used to make EESDs [9,10]. Research efforts in unconventional fabrication of EESDs include spray painting, paper, solid state, and elastic wire shaped EESDs [2][11–13]. EESD technologies aided in the fabrication of energy storage material as structural components for the objects that require power [14]. Structural EESDs, on the other hand, boost the overall system's energy and power capacity by acting as multifunctional building elements. [15]. Structural EESDs include reinforced electrode composites used as body panels for electric and hybrid automobiles [14–16]. Other structural EESD work is included into a panel cavity and employed as a multifunctional building element of the product. Research areas for EESDs take account of improving cycle life, increasing areal capacity, lower self-discharge rate, cost reduction, and increasing charging speed, etc. Research is also going on to use non-flammable electrolytes to increase the safety of the EESDs in various environments. Figure 1 depicts the overview of EESDs via AM.

Objectives

1. Development of experimental setup for fabrication of EESDs.
2. Study and analysis of the effects of controllable process parameters of material and AM process.
3. Design and development of EESDs using additive manufacturing setup.
4. Pilot scale demonstration of developed EESDs.

Keywords: Additive manufacturing, electrical characterization, electrochemical energy storage devices, surface morphology

Literature review

Because of the higher requirement for energy and power capacity, EESDs are used to power the majority of electronic devices, vehicles, and aeronautical devices [17]. Commercially available EESDs

consist of an anode, a separator, a cathode, and two current collectors fabricated as a package in cases based on the shape of the electrodes [18]. Commercial EESDs are fabricated in controlled environments as humidity with an EESD can negatively affect its performance, life span and safety. The dimension and profile of the EESDs have a major impact on their life span and the design parameters of the equipment they power. The life span and shape of transportable electronic gadgets, for example cell phones or laptops, is determined by the size of the EESDs. In the case of electrically powered vehicles, increment of areal and gravimetric capacity of the EESDs is a manufacturing challenge that affects vehicle cost and capability [2][19]. The requirement to maximise energy storage capacity requires the research and development of approaches to design and fabricate EESDs that can adapt to any shape and assist as structural part [17]. There have been noteworthy recent efforts to develop EESDs with unconventional shapes and structures to overcome form factor limits. Research efforts in unconventional fabrication include spray painting, paper, solid state, and elastic wire shaped EESDs [11–13]. Other approaches include various additive manufacturing processes like fused deposition modeling (FDM), ink jet printing (IJP), and direct ink writing (DIW) to develop EESDs. EESD technologies have aided in the fabrication of energy storage devices as structural components for objects that require power [2][14]. Structural EESDs, on the other hand, boost the whole system's power capacity by acting as a multifunctional structural member [15]. Structural EESDs include reinforced electrode composites used as body panels for electric and hybrid automobiles [14–16,20,21]. Other structural EESD work is included into a panel cavity and employed as a multifunctional building element of the product [22–25]. Research areas for EESDs take account of improving cycle life, increasing areal capacity, lower self-discharge rate, cost reduction, and increasing charging speed, etc. Research is also going on to use non-flammable electrolytes to increase the safety of the EESDs in various environments.

Using AM, some post processing steps in electrode fabrication can be eliminated, which will result in reduced production time and running cost [26,27]. Recent experimental studies show the effect of infill density, printing temperature, layer thickness and raster orientation on the mechanical properties of the fabricated part, which is useful for utilising the fabricated part as structural components [6,7,10,28]. The fabrication of EESDs using additive manufacturing indicates it has broad application

potential with improved energy density and higher safety [29]. The additive manufacturing methods have a wide material composite including various metal alloys, ceramics, and polymers, which offers the capability to fabricate higher mass loading of the active material [30]. The mixing of conductive materials with thermoplastics decreases the electronic and ionic conductivity of these materials, but the overall mixture is ready to fabricate the EESDs [2,31]. The fabrication of EESDs using an additive manufacturing approach is able to fabricate devices without the requirement for component assembly and chemical treatment [32]. To obtain good performance using the AM process, the mass ratio of active materials to conductive materials should be increased [33]. The electrode with conductive and active materials in its composition of 3D printable material enhanced the electrochemical properties of EESDs [34].

The fact that materials often utilised for additive manufacturing not ionic conductors like PLA, poses a significant challenge in the fabrication of EESDs. Chew et al. found that PLA can be utilized as a biodegradable solid-state polymer electrolyte by using lithium salts and oxide nanoparticles [28,35,36].

As ubiquitous as EESDs have become, it is important to describe their operation. A conventional EESD is comprised of a copper current collector, anode, separator, cathode, and an aluminium current collector in a casing that is filled with electrolyte [18]. An active material for lithium storage, conductive carbon for improved electron transport, and a polymer binder make up the electrodes. The active materials for commercial lithium based EESD is typically graphite for the negative anode and LCO (Lithium Cobalt Oxide) for the positive cathode. The separator is typically a porous polymer soaked in electrolyte whose purpose is to electrically isolate the anode from the cathode to prevent shorting. During charging, electrons from an external power source travel from the current collector, through the conductive carbon, to the graphite, where they reduce the lithium ions [37]. During charging, the lithium ions are inserted among the sheets of the graphite particle where they are stored in a 6:1 carbon to lithium ratio [38–40]. During discharge, a resistive load (cell phone, laptop, car) is connected to the battery where the lithium in the graphite is oxidised and electrons flow through the device to the cathode [41,42]. Lithium ions move through the separator in the cathode before being reduced and reinserted into the active material. There are three types of lithium storage methods within

active materials: intercalation and insertion, alloying, and conversion [43]. Alloying and conversion pose the potential to greatly increase the lithium storage capabilities of lithium-ion batteries. Alloying materials store lithium by alloying lithium metal atoms with Group IV elements such as silicon, which can store 10 times the amount of lithium per gram of material [43–46]. During the electrochemical reaction, the metal ion is reduced and replaced with a lithium ion [17,42].

Methodology

1. A thorough literature survey of the latest advancements in EESDs and AM technology for improved understanding and comparative study of the various EESDs and AM processes.
2. Study of different 3D printable materials like polymer composites to fabricate the EESDs. The polymer composites include various compositions of thermoplastic materials (like poly lactic acid, acrylonitrile butadiene styrene, and polypropylene), conductive materials (like carbon nanotubes and graphene), and active materials (like lithium cobalt oxide, lithium iron phosphate and lithium titanate oxide).
3. Experimentation with varying percentages of constituent materials.
4. Fabrication of EESDs from their constituent parts such as anode, cathode, separator, and current collectors.
5. Rigorous testing of fabricated parts includes mechanical testing (like tensile, compression, and impact test), chemical testing (like environmental, abuse, and stability test), electrical testing (like load, ionic conductivity, and cycle test), and surface morphology (like fractography using scanning electron microscopy and x-ray photoelectron spectroscopy).
6. Study and analysis for effects of controllable process parameters of AM process on mechanical, chemical, electrical and surface properties.

Likely impact of the research work

The proposed research will focus on improving and standardising additive manufacturing technology for EESDs. This will make India self-reliant in the field of additive manufacturing for EESDs. This will be a step towards a new era of growth and innovation in India and a new milestone being achieved in the Make in India campaign. The planned work's output would undoubtedly offer impetus to make the technology cost-effective so that it may thrive in the Indian market, making it an

outstanding job facilitator and promoting the establishment of start-ups and entrepreneurs in India. Significant research and development is required to investigate new additive manufacturing setup designs and fabrication process parameters in order to manufacture EESDs at a high throughput and low cost. It will provide an indigenous range of low-cost EESDs for various applications like electronic gadgets, electric and hybrid vehicles, aerospace electronics, electronic components of space craft and satellites, etc.

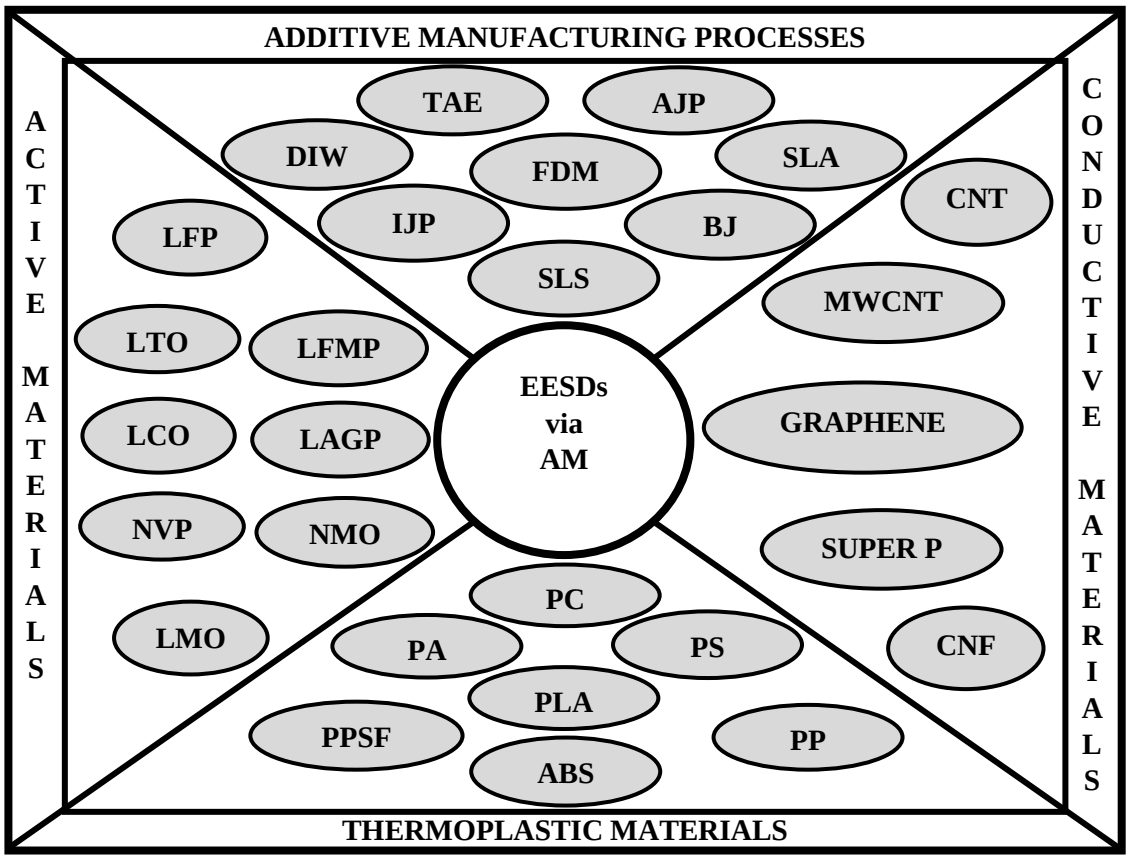

Figure 1: Overview of EESDs via AM

(Additive manufacturing processes, thermoplastic materials, conductive materials, and active materials. The already utilized AM processes includes ink jet printing (IJP), stereolithography (SLA), template assisted electrodeposition (TAE), selective laser sintering (SLS), fused deposition modeling (FDM), aerosol jet printing (AJP), binder jetting (BJ), and direct ink writing (DIW). Thermoplastic materials include polycarbonate (PC), poly lactic acid (PLA), polystyrene (PS), polyamide (PA), acrylonitrile butadiene styrene (ABS), polyphenylsulfone (PPSF), and polypropylene (PP). Conductive materials include graphene, multi-walled carbon nanotube (MWCNT), Super P, carbon nanofiber (CNF), and carbon nanotube (CNT). Active materials include lithium titanate oxide (LTO), lithium ferro phosphate (LFP), lithium aluminium germanium phosphate (LAGP), lithium cobalt oxide (LCO), lithium lanthanum zirconium oxide (LLZO), lithium manganese oxide (LMO), lithium ferro manganese phosphate (LFMP), sodium vanadium phosphate (NVP), sodium manganese oxide (NMO).

Expected output and outcomes of the research work:

(i) Proposed research and experimental studies will lead to innovation ready for pilot scale demonstration of fabricated EESDs.

(ii) It is expected that an understanding of the effects of process parameters from material preparation to additive manufacturing of the EESDs can provide potential for clean energy storage and ease of operation at reduced cost.

(iii) The proposed work will enable the fabrication of desired complex architectures of EESDs with precise control of the shape and size of the electrodes.

(iv) Reduction in dependence on the international market and making India self-reliant in the sector of EESDs through integrating additive manufacturing.

(v) High impact journal publications and the filing of patents.

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